A Description of the Initial Set of Analysis Products Available from the NEXRAD WSR-88D System

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Abstract

The NEXRAD program is deploying a network of approximately 160 weather radars throughout the United States and at selected overseas sites. The WSR-88D systems provide highly sensitive, fine-resolution measurements of reflectivity, mean radial velocity, and spectrum width data and generate up to 39 categories of analysis products derived from the base data every five to ten minutes. This paper provides an overview of the analysis products that are available on the WSR-88D systems. Primary uses and limitations of these products are discussed, and several examples are presented. A brief description of the WSR-88D system, including primary components, antenna scanning strategies, and product dissemination plans is also included.

1. Introduction

The Next Generation Weather Radar (NEXRAD) Program entails joint efforts of the United States' Departments of Commerce, Defense, and Transportation to develop, procure, and deploy an advanced Weather Surveillance Radar-1988 Doppler (WSR-88D) system that meets the common operational needs of the participating agencies. The WSR-88D systems are replacing meteorological radars currently employed by the National Weather Service (NWS), the U.S. Air Force, the Naval Oceanography Command, and the Federal Aviation Administration (FAA). The first WSR-88D system was installed near Oklahoma City, Oklahoma, during 1990. When the last installation is completed during 1996, at least 136 operational WSR-88D systems will be located in the contiguous United States. Others will be installed at sites in Alaska, Hawaii, the Caribbean, and at selected overseas military bases. The *Federal Meteorological Handbook No. 11, Part A* (1991) lists the locations for these radars. Figure 1 shows locations of the radars to be deployed in the contiguous United States. It also shows that network coverage at 3 km above site level is nearly continuous except for areas in the western United States caused predominantly by mountainous terrain that blocks the lower-level scans.

The NEXRAD program's network of WSR-88D systems ushers in a new greatly improved era in the remote sensing of the environment. These operational radars will provide the quality of high-resolution data and derived products available during the past only from research meteorological radars located at a few limited sites and time periods. They integrate advanced Doppler radar capabilities, real-time signal processing techniques, meteorological and hydrological algorithms, and automated product processing to generate numerous analysis products that are continually updated. These products will be available to more than 400 NEXRAD agency user sites via product display workstations. In addition, a predefined subset of products will be made available to many other users throughout the nation via the NEXRAD Information Dissemination Service (discussed in section 4) and recorded data archived at the National Climatic Data Center (Crum et al. 1993). Many potential users of WSR-88D products, however, have never seen an example or description of the products that will be available. The intent of this paper is to fill this void by providing an overview of the products that are available from the WSR-88D system.

2. WSR-88D system overview

WSR-88D systems generate three basic meteorological radar quantities: reflectivity, mean radial velocity, and spectrum width (a measure of the variability of radial velocities in the resolution volume). From these base data quantities, computer processing generates numerous meteorological analysis products.

The three major functional components of a WSR-88D system are radar data acquisition (RDA), also referred to as "radar," radar product generator (RPG), and principal user processor (PUP), along with the

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FIG. 1. WSR-88D network coverage at 10 000 ft (3.05 km) above site level for the contiguous United States. Hatched regions represent areas not covered below 3.05 km. Plus (+) notations represent locations of radar towers.

communications lines that link them. Figure 2 depicts the flow of base data from the RDA, through the RPG algorithms, to display on a PUP workstation as meteorological or hydrological products. Two columns of PUP products are shown. The first column lists the products that are produced from the hydrometeorological algorithms. The second column lists the products that display the base data in various formats. Only a brief system synopsis is presented in this paper; more detail may be found in *Federal Meteorological Handbook No. 11, Part D* (1992), Heiss et al. (1990), and Crum and Alberty (1993).

a. Radar data acquisition (RDA)

The RDA transmits microwave pulses and processes the returned signal into estimates of the three basic meteorological radar quantities: reflectivity, mean radial velocity, and velocity spectrum width. The RDA units consist of a tower, pedestal, antenna, fiberglass radome, klystron transmitter, receiver, signal processor, and status and control processor. Mean radial velocity and spectrum width data are provided out to a range of 230 km (124 nm) at a range resolution of 0.25 km and a data resolution of 0.5 m s^{-1}. Reflectivity data are provided out to 460 km (248 nm) at a range resolution of 1 km (but are displayed at this resolution only out to 230 km) and a data resolution of 0.5 dBZ (d$BZ = 10 \log_{10} Z$, where Z is in units of $mm^6 m^{-3}$). These base data are transmitted to the RPG where they are temporarily stored for use by the algorithms.

b. Radar product generator (RPG)

The RPG, where most of the data processing is done, invokes analysis programs (algorithms) that convert base data from the RDA into hundreds of meteorological and hydrological products (39 different categories of products) of various resolutions, data level intervals, and elevation angles in both graphic and alphanumeric form. These products are stored so they can be retrieved and distributed to multiple WSR-88D users via dedicated and dial-in communications lines.

c. Principal user processor (PUP)

The RPG passes products to the PUPs. A PUP is a workstation that displays and manipulates analysis products generated at the RPG. PUPs consist of a minicomputer with graphics processor, system and applications terminals, color graphic printer, color graphic monitors, a graphic selection tablet, and communications system. Color graphics are used to depict up to 16 intervals of quantitative values for parameters such as reflectivity, mean radial velocity, echo top heights, and precipitation accumulation amounts.

Products can be displayed on a PUP in many ways to assist the operator in assimilating the large amount of information available. Examples of the display options available to the PUP operator are magnification of displays by a factor of 2, 4, or 8; display of four products per screen; display of up to 72 images in a time lapse; selection of various combinations of high-resolution map backgrounds and overlays; and definition of two distinct alert areas that will trigger an audible alarm if operator-selected meteorological criteria are met.

3. Operational considerations

a. Adaptable parameters

The WSR-88D data processing and algorithm software contains externally defined variables (adaptable parameters) that optimize the system for varying geographical, climatological, and site-specific conditions and adjust the radar for different agency operational requirements. About 400 parameters are used for optimizing the performance of the meteorological algorithms. The parameters used in the reflectivity–rainfall rate relationship, or shear criteria for triggering the mesocyclone algorithm, are examples of adapt-

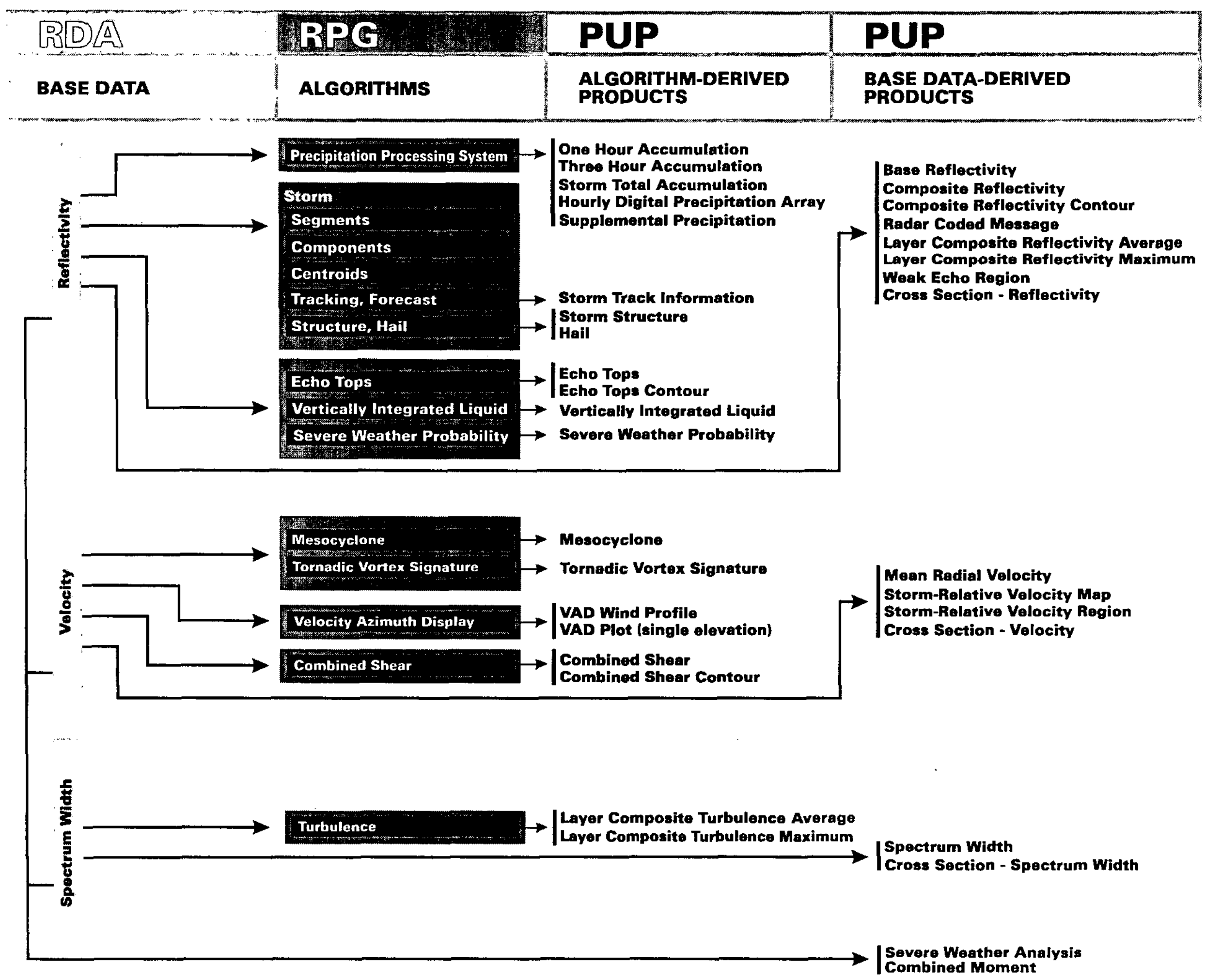


FIG. 2. Data flow through the WSR-88D system. Diagram illustrates the flow of base data from the radar data acquisition (RDA) to display as an analysis product for the operator at the principal user processor (PUP). The groups of hydrometeorological algorithms executed in the radar product generator (RPG) are shown.

able parameters. Other examples are described in section 5.

b. Factors associated with distance from radar

The ranges in which the WSR-88D processes data are 230 km (124 nm) for velocity and spectrum width measurements and 460 km (248 nm) for reflectivity measurements. Due to beam widening and increasing height above the earth with increasing range, WSR-88D algorithms have been designed to process data with resolutions that are consistent with spatial scales of relevant meteorological phenomena. For example, the precipitation algorithm estimates rainfall and the velocity-based algorithms produce velocity products out to 230 km. The storm identification and centroid tracking algorithm processes data out to 345 km (186 nm). Between 345 km and 460 km (248 nm), no derived product algorithms are active, but reflectivity products are still available.

c. Antenna scanning strategies

The antenna of each WSR-88D system continuously monitors its environment in a preprogrammed sequence of 360° azimuthal sweeps at various elevation angles. A complete sequence of azimuthal sweeps is defined as a "volume scan." Initially, WSR-88D systems will have the capability of using four volume scan strategies (one at a time). There are two clear air strategies in which the antenna completes 360° azimuthal sweeps at five elevation angles (0.5° to 4.5°) every ten minutes. A precipitation strategy (nine elevation angles every six minutes) and a severe weather strategy (14 elevation angles every five minutes) both operate at elevation angles between 0.5° and 19.5°. Other strategies may be implemented in the future as operational requirements dictate.

Figure 3 illustrates beamwidth and height above the earth's surface as a function of range for the 14 elevation angles used in the severe weather strategy. A "cone of silence" exists close to the radar. For instance, at 35 km, weather phenomena above approximately 12 km cannot be detected by azimuthal sweeps at the highest (19.5°) elevation angle. Figure 3 also illustrates the gaps that exist between azimuthal sweeps for elevation angles higher than 6.2°.

4. NEXRAD Information Dissemination Service

Although exceptions may occur, private organizations and government agencies (other than the three NEXRAD agencies) will not be provided real-time direct access to WSR-88D data. Therefore, a NEXRAD Information Dissemination Service (NIDS) has been established for the distribution of selected WSR-88D base and derived products to external users. Up to four private sector data providers will access each WSR-88D system in the contiguous United States and offer data services to subscribers (e.g., TV stations and private forecasting companies). A basic set of 13 WSR-88D products will be offered to subscribers in an unaltered format (Table 1). In addition, providers will be able to produce extra "value-added" products that are derived from the unaltered products and offer these to their subscribers as well. Baer (1991) gives a more detailed description of NIDS.

5. WSR-88D products

Meteorological and hydrological algorithms residing in the RPGs generate up to 39 categories of data analysis products every volume scan. Some of these algorithms display the base data in various formats, while others analyze the base data to generate derived products. The 39 product categories are summarized in Table 1 in terms of specifications, availability to NIDS, and archival at the National Climatic Data Center (NCDC). Crum et al. (1993) describe the capabilities and plans for recording of WSR-88D base data (level II) and products (level III).

The products may be divided into two groups: those created for each constant elevation angle azimuthal sweep (elevation angle products) and those constructed with base data from two or more azimuthal sweeps within a volume scan (volume products). Many different combinations of products are possible within a single product category (e.g., data resolutions, data levels, and elevation angles). For example,

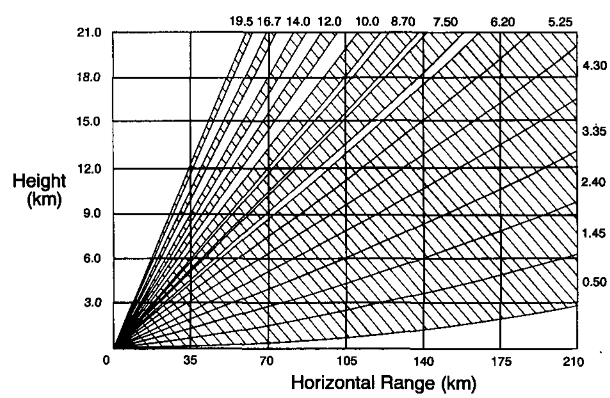


FIG. 3. Beamwidth (for 0.95° beam) and height above the earth's surface related to range from the radar for the 14 elevation angles (0.50° to 19.5°) used in the WSR-88D severe weather antenna scanning strategy. Horizontal axis is range from radar (km). Vertical axis is height above the earth's surface (km) (*Federal Meteorological Handbook No. 11, Part C,* 1991).

ELEVATION ANGLE PRODUCTS	Spatial Resolution		Number of Data Levels Available	MAX Range of Product Computations (km)	Product Coverage (Dimensions)		Archived at NCDC (Level III)	NIDS Product
	km X	km or deg			Radius (km)	km X km		
Base Reflectivity (R)	1	1°	8 and 16	230	230	—	Yes (0.5° TILT)	Yes (4 TILTS) 16 DATA LEV
	2	1°	8 and 16	460	460	—	—	Proposed (1 TILT) 16 DATA LEV
	4	1°	8 and 16	460	460	—	—	—
Mean Radial Velocity (V)	0.25	1°	8 and 16	60	60	—	Yes (0.5° TILT)	—
	0.5	1°	8 and 16	115	115	—	—	—
	1	1°	8 and 16	230	230	—	Yes (0.5° TILT)	Yes (4 TILTS) 16 DATA LEV
Spectrum Width (SW)	0.25	1°	8	60	60	—	Yes (0.5° TILT)	—
	0.5	1°	8	115	115	—	—	—
	1	1°	8	230	230	—	Yes (0.5° TILT)	—
Storm-Relative Mean Radial Velocity Map (SRM)	1	1°	16	230	230	—	—	Proposed (2 TILTS)
Storm Relative Mean Radial Velocity Region (SRR)	0.5	1°	16	230	—	50 x 50	—	—
Combined Shear (CS)	0.5	0.5	16	115 - 163	—	230 x 230	—	—
	1	1	16	115 - 163	—	230 x 230	—	—
	2	2	16	115 - 163	—	230 x 230	—	—
	4	4	16	115 - 163	—	230 x 230	—	—
Combined Shear Contour (CSC)	0.5	0.5	5	115 - 163	—	230 x 230	—	—
	1	1	5	115 - 163	—	230 x 230	—	—
	2	2	5	115 - 163	—	230 x 230	—	—
	4	4	5	115 - 163	—	230 x 230	—	—
Severe Weather Analysis (SWA)								
(SWR) Reflectivity	1	1°	16	230	—	50 x 50	—	—
(SWV) Velocity	0.25	1°	16	230	—	50 x 50	—	—
(SWW) Spectrum Width	0.25	1°	8	230	—	50 x 50	—	—
(SWS) Radial Shear	0.5	1°	16	230	—	50 x 50	—	—
Combined Moment (CM)								
Reflectivity	1	1°	8	230	—	25 x 25	—	—
Velocity	0.5	1°	N/A	230	—	25 x 25	—	—
Spectrum Width	0.5	1°	N/A	230	—	25 x 25	—	—

N/A means Not Applicable

TABLE 1. Products and associated specifications available on the WSR-88D systems. (Continued on next page.)

the base reflectivity product can be displayed with three different resolutions and two data-level options that yield six different reflectivity products for each constant elevation angle azimuthal sweep. A total of 84 unique base reflectivity products are available since six products can be generated on 14 different elevation angles in the severe weather antenna scanning strategy.

VOLUME PRODUCTS	Spatial Resolution km	X km or deg	Number of Data Levels Available	MAX Range of Product Computations (km)	Product Coverage (Dimensions) Radius (km)	Product Coverage (Dimensions) km X km	Archived at NCDC (Level III)	NIDS Product
Composite Reflectivity (CR)	1	1	8 and 16	230	230	—	—	—
	4	4	8 and 16	460	460	—	Yes	Yes
Composite Reflectivity Contour (CRC)	1	1	16	230	230	—	—	—
	4	4	16	460	460	—	—	—
Echo Tops (ET)	4	4	16	230	230	—	Yes	Yes
Echo Tops Contour (ETC)	4	4	16	230	230	—	—	—
Weak Echo Region (WER)	1	1	8	230	—	50 x 50	—	—
Layer Composite Reflectivity Average (LRA)	4	4	8	230 - 324	—	460 x 460	—	—
Layer Composite Reflectivity Maximum (LRM)	4	4	8	230 - 324	—	460 x 460	—	Yes
Layer Composite Turbulence Average (LTA)	4	4	8	150 - 213	—	300 x 300	—	—
Layer Composite Turbulence Maximum (LTM)	4	4	8	150 - 213	—	300 x 300	—	—
One Hour Precipitation (OHP)	2	2	16	230	230	—	Yes	Yes
Three Hour Precipitation (THP)	2	2	16	230	230	—	—	Yes
Storm Total Precipitation (STP)	2	2	16	230	230	—	Yes	Yes
One Hour Digital Precipitation Array (DPA)	Approx 4 (1/40 LFM)	Approx 4 (1/40 LFM)	100	230	230	—	Yes	Yes
Supplemental Precipitation Data (SPD)	Approx 40 (1/4 LFM)	Approx 40 (1/4 LFM)	8	230	—	13 x 13 of 1/4 LFM	Yes	—
Velocity Azimuth Display (VAD)	N/A	N/A	7	1 - 230	—	—	—	—
Velocity Azimuth Display Wind Profile (VWP)	N/A	N/A	5	1 - 230	—	—	Yes	Yes
Reflectivity Cross Section (RCS)	1	0.5	8 or 16	up to 230	—	—	—	—
Velocity Cross Section (VCS)	1	0.5	8 or 16	up to 230	—	—	—	—
Spectrum Width Cross Section (SCS)	1	0.5	8	up to 230	—	—	—	—
Vertically Integrated Liquid (VIL)	4	4	16	230	230	—	Yes	Yes
Severe Weather Probability (SWP)	28	28	N/A	230	230	—	Yes	—
Hail Index (HI)	N/A	N/A	5	230	230	—	Yes	—
Mesocyclone (M)	N/A	N/A	3	230	230	—	Yes	—
Tornadic Vortex Signature (TVS)	N/A	N/A	N/A	230	230	—	Yes	—
Storm Tracking Information (STI)	N/A	N/A	N/A	345	345	—	Yes	—
Storm Structure (SS)	N/A	N/A	N/A	345	345	—	Yes	—
Radar Coded Message (RCM)	Approx 10 (1/16 LFM)	Approx 10 (1/16 LFM)	9	460	460	—	Yes	—

TABLE 1 (cont.). Products and associated specifications available on the WSR-88D systems.

A brief description of each product follows, along with comments about their primary uses and limitations and references to figure numbers when examples exist. The discussion is meant to provide an introductory overview of each product and is not comprehensive. The products are described in the same order as they appear in Table 1. A one- to three-letter abbreviated product identifier is listed immediately after (in parentheses) the first use of each product name. Examples of some of the products are presented in section 6 (Figs. 4–12). Those figure numbers are referenced at the end of each associated product description in this section as applicable. Figure numbers will not appear in ascending order in this section, because they are presented in order in section 6. *Federal Meteorological Handbook No. 11, Part C* (1991), provides more information on the WSR-88D products.

a. Elevation angle products

Base reflectivity (R) depicts a full 360° azimuthal sweep of echo intensity data and is available for every elevation angle that is sampled in a volume scan. The product is displayed in polar coordinates at 1° x 1-km resolution to a range of 230 km, or at 1° x 2-km or 1° x 4-km resolution out to 460 km, and is available with 8 or 16 reflectivity data-level intervals (e.g., 5 to <10 dB*Z*, 10 to <15 dB*Z*, 15 to <20 dB*Z*). The data-level values range from −28 to ≥+28 dB*Z* when the radar is operating in the high-sensitivity, clear air scanning strategy, and +5 to ≥+75 dB*Z* (+5 to ≥+57 dB*Z* for eight data-level intervals) when the precipitation or severe weather scanning strategy is active. Base reflectivity is used to estimate hail potential, to determine storm structure, and to locate boundaries and precipitation cores. The sensitivity of the WSR-88D system is much greater than existing operational radars such as the WSR-57 (−8 dB*Z* versus +13 dB*Z* at a range of 50 km). This increased sensitivity has resulted in the detection of cold fronts, drylines, thunderstorm outflow boundaries, birds, insects, and smoke plumes. Very light precipitation, both snow and drizzle, are readily detected, as are ice crystals in mid- and high-level clouds. Examples of the base reflectivity product are illustrated in Fig. 4 and the cover figure.

Mean radial velocity (V) depicts a full 360° azimuthal sweep of radial velocity data and is available for every elevation angle sampled. The product is displayed in polar coordinates at 1° x 0.25-km resolution to a range of 60 km, 1° x 0.5-km resolution to 115 km, and 1° x 1-km resolution to 230 km, and is available with 8 or 16 data-level intervals (in knots). This product portrays the radial component of the wind (either toward or away from the radar) with colors changeable at the PUP (adaptable parameter). Forecasters use this product in estimating wind speed and direction, locating boundaries, and determining regions of significant shear (i.e., convergence, divergence, mesocyclones, and tornadic vortex signatures).

A limitation of the mean radial velocity product is that winds perpendicular to the radar beam are depicted with a radial velocity of zero. Range folding and incorrect velocity dealiasing are other limitations that contaminate the product at times. Range folding occurs when the system cannot distinguish whether returned energy is from the most recently transmitted pulse or from a previous pulse that is returned from a more distant weather phenomena (called "second trip," "third trip," etc., echoes). If two echoes are overlaid due to multiple-trip returns, the velocity data are assigned to the range of the stronger echo. The judicious setting of the echo power comparison threshold (adaptable parameter) can result in a significant reduction in range-folded data.

If two echoes are overlaid due to multiple-trip returns, the velocity data are assigned to the range of the stronger echo. The judicious setting of the echo power comparison threshold (adaptable parameter) can result in a significant reduction in range-folded data.

Spectrum width (SW) depicts a full 360° azimuthal sweep of spectrum width data and is available for every elevation angle sampled. The product is displayed in polar coordinates with resolutions and ranges identical to those of mean radial velocity but is available only with eight data levels (in knots). It provides a measure of the variability of the mean radial velocity estimates due to wind shear, turbulence, and/or the quality of the velocity samples. It is used to locate boundaries, estimate turbulence, and check the reliability of radial velocities. It may also be a useful tool for locating mesocyclones and tornadoes since significant shear is usually associated with these features. Weak signal returns near the noise threshold will lead to erratic spectrum width data.

Storm-relative mean radial velocity map (SRM) is similar to the base velocity product except that it subtracts the average motion of *all* identified storms as determined by the storm track information (STI) algorithm *or* a storm motion selected by the operator. This product is available for each elevation angle that is sampled; however, the product is available with only one range (230 km), resolution (1° x 1 km), and number of data-level intervals (16). It uses the maximum base velocity from four 0.25-km range resolution bins that are components of a single 1-km product resolution volume. This product is used to detect shear regions (such as mesocyclones, tornadic vortex signatures, and divergence signatures) that might be obscured by storm motion and is most effective with fast-moving storms. The product will not present reliable information for a given storm if the average storm

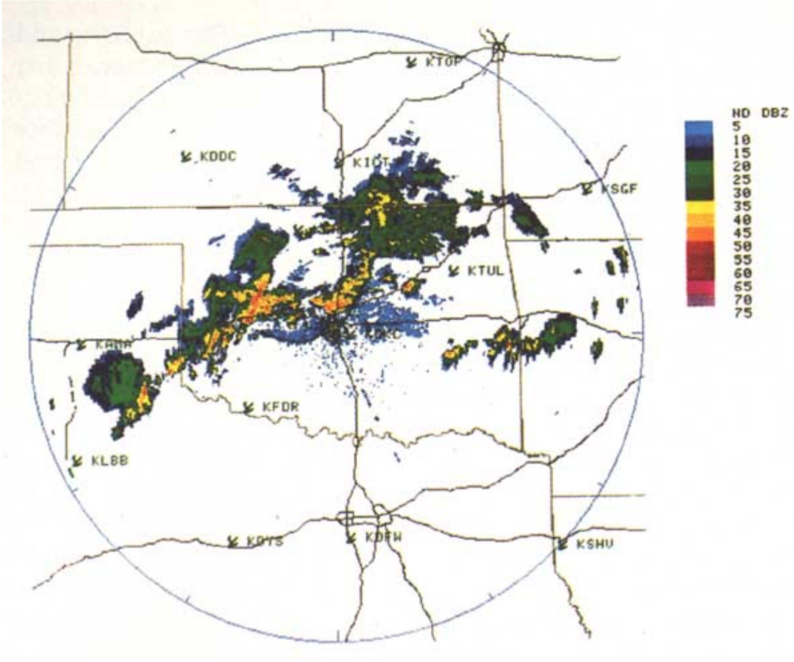


FIG. 4. Norman, Oklahoma, WSR-88D base reflectivity product at 22:18 UTC 1 September 1989. The color table on the right depicts the intervals of reflectivity in units of dBZ. The elevation angle is 0.5°, range of coverage is 248 nm (460 km), and resolution is 1° x 1.1 nm (2 km). Maps displayed are 248-nm (460-km) range ring, state boundaries, interstate highways, and WSR-88D sites. The maximum reflectivity is 57 dBZ.

motion from the STI algorithm is not representative of that storm (e.g., a vector average of storms moving in a widely divergent pattern would be unrepresentative of at least some of the storms).

Storm-relative mean radial velocity region (SRR) is similar to the SRM product with a few exceptions. First, it is a "window" product that covers a 50-km x 50-km region that the operator can specify anywhere within a 230-km radius of the radar. The product resolution (1° x 0.5 km) is also better than the SRM. The storm motion subtracted for the SRR product defaults to the motion of the storm closest to the product center or can be input by the operator. The operator typically centers the SRR product on a specific thunderstorm at several elevation angles to examine the three-dimensional storm-relative flow. Figure 9 shows examples of the SRR product for four elevation angles (from the same volume scan) centered at the same location.

Combined shear (CS) depicts combined radial and azimuthal shear (into single-filtered shear values) of the mean radial velocity on a 230-km x 230-km Cartesian grid (centered at the radar location) displayed with 16 data levels. This product is available in four different resolutions, and for all elevation angles. Due to its high computational load on the system, however, only one CS product may be generated per volume scan. It is designed to identify low-level wind shear associated with gust fronts, downbursts, and mesoscale rotational phenomena. Extensive filtering of both velocity and shear data may remove significant small-scale phenomena of less than 4 km.

Combined shear contour (CSC) is a contoured version of the CS product that is displayable alone or as an overlay on reflectivity or velocity products. It is generated, on user request, for the same elevation angle selected for the CS product. As an overlay, it can highlight shear zones on velocity products.

Severe weather analysis (SWA) provides, *at the highest resolution available,* four separate products: reflectivity (SWR), mean radial velocity (SWV), spectrum width (SWW), and radial shear (SWS). The four products are mapped to the same 50-km x 50-km grid within 230 km of the radar location and are normally displayed on the same screen in a four-quadrant presentation. Each one of the four products, however, can also be displayed on a full screen. The four-component SWA can be automatically generated when specified alerts (e.g., a mesocyclone) are triggered and will be centered at the azimuth/range and the elevation angle nearest the "critical altitude" for the meteorological phenomenon causing the alert. The product can also be generated for a user-specified elevation angle and geographical center point. The highest resolution base velocity and spectrum width products (1° x 0.25 km) allow data presentations only out to 60 km, whereas the SWA velocity and spectrum width can be generated anywhere within 230 km of the radar with the 1° x 0.25-km resolution.

Combined moment (CM) combines the reflectivity, mean radial velocity, and spectrum width data into a single 25-km x 25-km "window" product centered at any geographic center point within 230 km of the radar for any azimuthal sweep. The product is displayed with range as the ordinate and azimuth as the abscissa. Reflectivity is displayed as a gridded image at full radar resolution (1 km) in eight data levels. Velocity and spectrum width are depicted by arrows superimposed over the reflectivity image at a resolution of 1° x 0.5 km. The direction that the arrows point determines whether the radial velocity is inbound or outbound and also the approximate speed. The size of the arrowhead is proportional to the spectrum width values. The CM product may be used to more effectively determine the strength of the winds in a mesocyclone or the storm-top divergence since the velocity depicted [±100 kt (51.4 m s^{-1})] is not limited to the narrower range of default values defined on the mean radial velocity products (although these can be changed). Due to the range versus azimuth format presentation, the reflectivity field is distorted, and geographical map backgrounds cannot be overlaid onto the display. Interpretation of this product requires considerable experience.

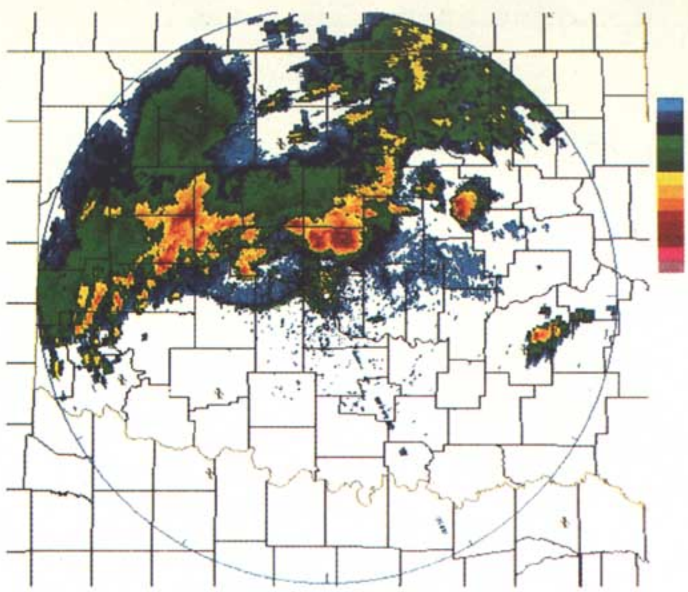
b. Volume products

Composite reflectivity (CR) depicts the maximum reflectivity found on any constant elevation angle azimuthal sweep of a volume scan projected onto each Cartesian grid box. Therefore, adjacent grid boxes could contain reflectivity values that were projected from different heights within the storm. The grid resolutions are 1 km x 1 km or 4 km x 4 km with corresponding areal coverages of 230-km or 460-km radius from the radar location, and with 8 or 16 data-level intervals (dBZ). A table called the "combined attribute table" is an additional option and provides valuable information concerning vital storm characteristics from the storm series algorithms (e.g., storm tops, maximum mean radial velocity and reflectivity, existence of hail and mesocyclones). The CR product is most useful in displaying the highest reflectivities in a storm without searching all of the available elevation angles. The major limitations are that significant low-level signatures (e.g., hook echoes and weak echo notches) that may be present in a single azimuthal sweep may not be distinguishable. Also, the heights of the maximum reflectivity values are not displayed. Figures 5a and 5b show examples of the composite reflectivity product.

Composite reflectivity contour (CRC) is similar to the CR except that fields of color imagery data are converted to a contoured format instead. The contour interval and number of contours are adaptable.

Echo tops (ET) is a 16 data-level product that displays echo-top heights

(a)



(b)

STM ID	AZ RAN		TVS	MESO	HAIL	DBZM HGT		VLOW	STM TOP	FCST MVMT		MW VOL
04	11	28	NO	YES	PRO	66	39.3	43	51.28	265	17	23219
T	296	67	NO	NO	PRO	63	20.0	25	50.84	262	12	28636
L	57	69	NO	NO	POS	63	28.4	17	48.28	259	10	3225
19	290	37	NO	NO	POS	53	21.8	12	25.16	238	19	442

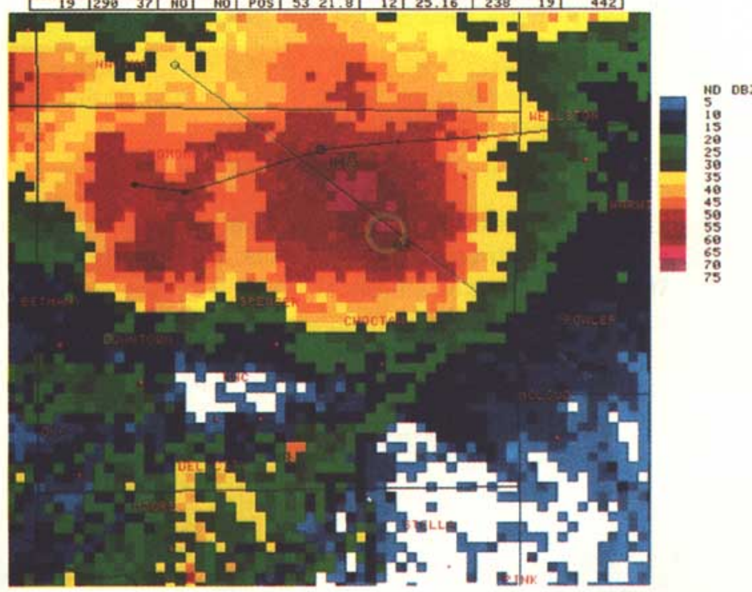


Fig. 5. Norman, Oklahoma, WSR-88D composite reflectivity products at 22:18 UTC 1 September 1989. The color tables on the right depict the intervals of reflectivity in units of dBZ. (a) Range of coverage is 124 nm (230 km) and resolution is 0.54 nm x 0.54 nm (1 km x 1 km). Maps displayed are 124-nm (230-km) range ring, state and county boundaries, and airports (symbol " ⚕ "). The maximum reflectivity is 69 dBZ. (b) Centered at 16°/20 nm (37 km) from radar and resolution same as (a). Magnification is 8x. Maps displayed are county boundaries and city names. Product overlays are mesocyclone, hail index, and storm tracking information associated with storm 04. Diagonal blue line is slice selected by operator for cross section products shown in Figs. 6 and 7. Storm attribute table is located at top, which shows information for four storms (including storm 04 displayed here). The table shows azimuth (deg)/range (nm) of the storm centroid (relative to radar), whether a tornadic vortex signature, mesocyclone, or hail have been indicated, the maximum reflectivity (dBZ) and the height (kft) of the maximum reflectivity, maximum mean radial velocity detected at the lowest height sampled within the storm (kt), storm-top height (kft), forecast direction (from which storm is moving) and speed (deg/kt), and mass (Gg).

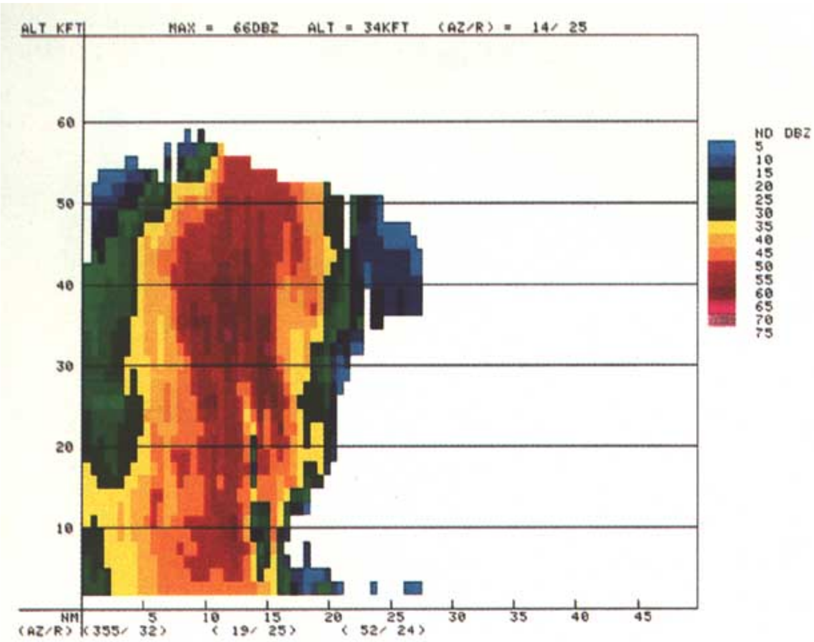


FIG. 6. Norman, Oklahoma, WSR-88D reflectivity cross section product at 22:18 UTC 1 September 1989. Horizontal axis is distance (nm); vertical axis is altitude (kft) above the radar. Slice depicted is 355°/32 nm (59 km) to 52°/24 nm (44 km) using the radar as the reference point. Slice is shown graphically in Fig. 5b. The color table on the right depicts the intervals of reflectivity in units of dBZ. The maximum reflectivity is 66 dBZ at 34 kft (10.4 km) located 14°/25 nm (46 km) from the radar.

(kft) based on the highest elevation angles at which ≥18-dBZ (adaptable threshold) reflectivities are detected. The echo tops are referenced to mean sea level (MSL) on a 4-km x 4-km Cartesian grid within 230 km of the radar. This product is useful in identifying the more significant storms by locating the highest tops. A circular "stair-step" appearance often occurs due to volume coverage pattern limitations associated with antenna scanning strategies.

Echo-tops contour (ETC) is a contoured version of the ET product. The contour interval and the base contour value are adaptable.

Weak echo region (WER) depicts reflectivity data for up to eight elevation angles for an operator-selected location as a set of stacked planes (50 km x 50 km) that gives a pseudo-three-dimensional presentation of a storm. Reflectivity is displayed at the best resolution (1 km) with eight data-level intervals and can be generated anywhere within 230 km of the radar. The operator can select the specific eight elevation angles (from choices available for the particular antenna volume scan strategy in use) to be displayed. The planes are presented in ascending order, with the lowest plane representing the lowest elevation angle. The product was designed to depict storm tilt and identify storms with weak echo regions and bounded weak echo regions. Although shown as horizontal planes, altitudes vary within the planes of the product, especially at the higher-elevation angles and greater distances (due to curvature of

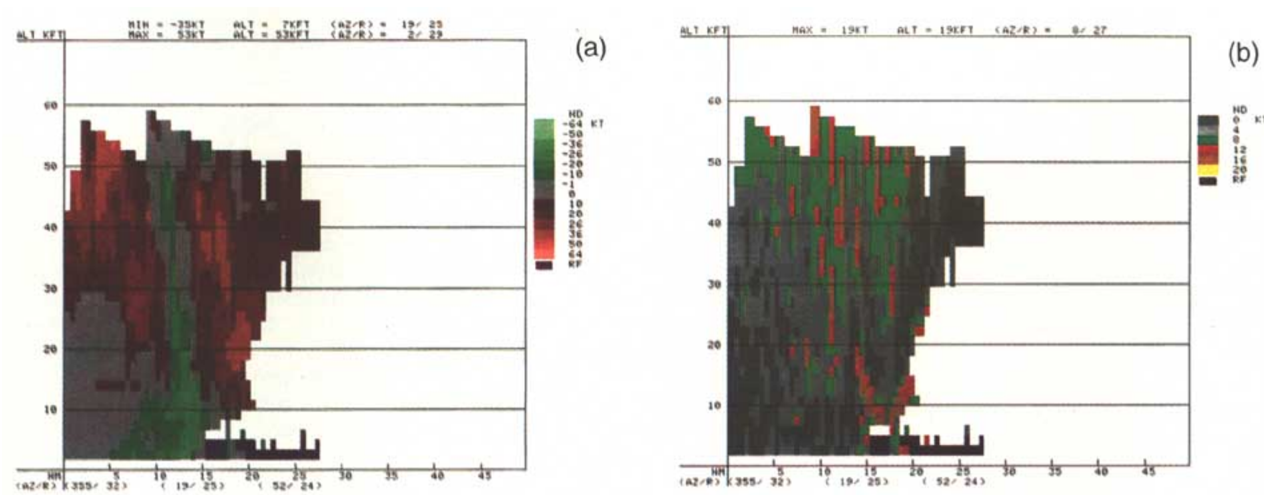


FIG. 7. Norman, Oklahoma, WSR-88D velocity (a) and spectrum width (b) cross section products at 22:18 UTC 1 September 1989. Horizontal axis is distance (nm); vertical axis is altitude (kft) above the radar. Slice is the same as defined in Fig. 6 and is shown graphically in Fig. 5b. The color tables on the right depict the intervals of velocity (kt) for (a), and the intervals of velocity spectrum width (kt) for (b). Magnitudes, altitudes, and locations (azimuth/range) of the strongest inbound and outbound mean radial velocities (a) and maximum spectrum width values (b) are printed at the top.

the earth) from the radar. An example of a WER product is shown in Fig. 8.

The layer composite reflectivity average (LRA) **and maximum** (LRM) products are available for three layers (defined by adaptable parameters). Default values for the layers are surface to 7.3 km MSL, 7.3 km to 10.1 km MSL, and 10.1 km to 18.3 km MSL. Eight data levels of reflectivity are depicted on a 4-km x 4-km resolution Cartesian grid (460 km x 460 km) centered on the radar for each layer. The value applied to each layer grid point is determined from the vertically projected data from the associated azimuthal sweeps, by either computing an average (LRA) or taking the maximum (LRM) of the individual values within the layer grid box. This product is intended to be used by aviation meteorologists in support of routing air traffic. It is also useful in determining storm trends by comparing the midlevel product to a low-elevation angle base reflectivity product. Altitude limitations associated with radar beam scanning may result in missing significant low-level reflectivity at further distances on the low-layer product and high-level reflectivity at closer distances on the high-layer product.

The layer composite turbulence average (LTA) **and maximum** (LTM) products are available for three layers as described for LRA and LRM. Eight data levels of turbulence intensity values computed by a turbulence algorithm operating on spectrum width data are depicted on a 300-km x 300-km grid centered on the radar for each layer. The value applied to each layer grid point is a composite obtained in a manner similar to that used for LRA and LRM. The LTA and LTM products are designed to help estimate the strength of turbulent air motions. As with the LRA and LRM, these products were designed for use by the aviation community.

The next five products listed in Table 1 are the precipitation products. These products are generated following a substantial number of quality control steps in processing base reflectivity data from the lowest four elevation angles into rainfall rate and accumulation estimates. Three graphical and two digital products are generated.

The graphical displays are **one-hour precipitation** (OHP), **three-hour precipitation** (THP), and **storm total precipitation** (STP) accumulation products. These products use a Cartesian grid with a 2-km x 2-km resolution. Each product depicts rainfall accumulations within 230 km of the radar and displays 16 accumulation data levels. The OHP product is updated each volume scan after precipitation is detected. The THP provides rainfall accumulation for the present clock hour plus the previous two clock hours and is updated once per hour. The STP is available from the first volume scan with detected precipitation and continuously updates each volume scan. The OHP and STP products will be identical during the first hour following the detection of precipitation, except for variations due to differences in the way the 16 accumulation data-level intervals are defined on each product. Short-term forecasts of precipitation tracks and trends can be developed when the STP is viewed in time lapse mode. The STP resets to zero accumulation when no precipitation has been detected by the radar over the previous hour. Examples of the STP product for two time intervals (with the same starting time) are shown in Fig. 11.

Short-term forecasts of precipitation tracks and trends can be developed when the STP is viewed in time lapse mode. The STP resets to zero accumulation when no precipitation has been detected by the radar over the previous hour.

A fourth precipitation product, the **digital precipitation array** (DPA), is a one-hour digital array accumulation product that is not available to PUP users. It uses a 1/40 limited fine-mesh (LFM) grid (approximately 4 km x 4 km) and has 100 data levels. It is for use in NWS Forecast Office computers for follow-on precipitation processing (inclusion of additional raingage and satellite data and quality control checks). This second processing (stage 2) dataset is then passed on to river forecast centers (RFCs) where combining of other stage 2 products from all radars within their area of hydrologic responsibility is performed and final adjustments are made (stage 3) to the precipitation data fields. These final products are used by RFC staff, flood forecasters, and water management specialists to help them with important hydrological decisions (Shedd and Smith 1991; Hudlow 1990). Stage 2 and stage 3 processing is conducted on computers that are external to the WSR-88D. The DPA will also be available to the U.S. Army Corps of Engineers for follow-on processing and to the NIDS providers.

A **supplemental precipitation data** (SPD) product that provides information regarding the performance of the precipitation processing system of algorithms to computers external to the WSR-88D unit is generated each volume scan. Examples of information the SPD contains are total number of isolated bins, bias estimates, and gauge accumulations. For each precipitation rate scan generated, it also contains instantaneous area-averaged precipitation rates on a 13 x 13 grid with resolution boxes equal to one-fourth of the LFM. The primary purpose of the SPD is for system performance checks. The supplemental data are also appended to the DPA.

The **velocity azimuth display** (VAD) is a graphical plot of mean radial velocity versus azimuth angle for a particular altitude. The best-fit sine wave is overlaid on the plot of the velocity points if a sufficient number of data points exist. This sine wave is used to compute the wind speed and direction for that particular height. Once the sine wave is fitted to the data, the statistical error and symmetry (differences between inbound and outbound radial velocities) are computed. If statistical error or symmetry thresholds are exceeded, the algorithm does not compute the wind speed and direction, although the operator can still view the data. This product will be used most often to check suspicious or missing wind data on the VAD wind profile. Deformations in the wind field (e.g., fronts, troughs) over the area of analysis can bias the analysis.

Velocity azimuth display wind profile (VWP) displays mean horizontal winds (computed from the VAD algorithm for each level) on a time versus height chart. Up to 30 conventional wind barbs from the surface to 21 km can be plotted. This product displays the latest wind/height profile, and the 10 most recent wind/height profiles (at 5- to 10-minute intervals). The product is useful in the identification of low- and high-level jets, thermal advection patterns, vertical wind shear, depths of frontal surfaces, and the development of isentropic lift situations. The product use will be limited at times due to the lack of scatterers or when statistical and symmetry errors are exceeded in the VAD processing stage. Figure 12 shows an example of the VWP product.

The **reflectivity cross section** (RCS), **velocity cross section** (VCS), and **spectrum width cross section** (SCS) products provide a vertical cross section of either reflectivity, mean radial velocity, or spectrum width. The cross sections are similar to range–height indicator slices observed on conventional radars but are not confined to alignments along radar radials. Instead, the operator defines any two end points within 230 km of the radar that are less than 230 km apart. Each product is displayed on a grid with heights up to 21 km depicted on the vertical axis, and distance up to 230 km on the horizontal axis. Their resolutions are 1 km horizontal and 0.5 km vertical; however, data collected from noncontiguous azimuthal sweeps produce coarser vertical resolutions, since data gaps are filled by vertical and horizontal interpolation.

The RCS is used to examine storm structure features such as overhang, tilt, weak echo regions, and bounded weak echo regions. VCS is primarily used in conjunction with the RCS to relate the reflectivity structure and kinematics of a storm or storm complex. The product is also used to examine storm-top divergence and analyze the vertical extent of mesocyclones. The SCS is used to verify features on the RCS and VCS products and for aviation applications in determining the vertical extent of turbulent zones. Figures 6 and 7 show an example of each of these cross sections for the same time and location.

The RCS is used to examine storm structure features such as overhang, tilt, weak echo regions, and bounded weak echo regions. VCS is primarily used in conjunction with the RCS to relate the reflectivity structure and kinematics of a storm or storm complex.

Vertically integrated liquid (VIL) values represent reflectivity data converted into liquid water equivalent via an empirically derived relationship that assumes that all reflectivity returns are from liquid water. Values are derived for each 4-km x 4-km grid box for each elevation angle sampled within a 230-km radius of the radar, then vertically integrated. In the central plains, VIL values have been found to be good indicators of the presence of both small and large hail (Winston and Ruthi 1986). Underestimates of VIL occur with fast-moving storms or storms that are strongly tilted, due to high reflectivities aloft being spread into other grid boxes, and also for storms that are incompletely scanned due to their close proximity to the radar. Overestimates may occur for storms beyond 200 km since the algorithm extrapolates liquid water estimates from the lowest azimuthal sweep below the beam down to the surface. An example of the VIL product is shown in Fig. 10.

Severe weather probability (SWP) displays numerical values relating the probability that a particular storm is severe. The algorithm uses a statistical regression equation that analyzes output from the VIL algorithm. The product is used principally to highlight the most significant storms. The empirically derived regression equations use coefficients that are adaptable.

For each storm identified by the storm series algorithms, the **hail index** (HI) product provides an indication of whether the storm structure is conducive to the production of hail. It is updated concurrently with the storm structure product. The output from the product is a green hail symbol (that indicates "probable" or "positive" hail potential) overlaid on any geographically based image product. It is also available in alphanumeric form. The algorithm assumes that all storm components are circular and the center of mass is at the geometrical center of the circle. Large deviations from this assumption may result in errors in the determination of the hail indicators that are based on storm overhang and tilt.

The **mesocyclone** (M) product is designed to display information regarding the detection of three types of azimuthal shear patterns: uncorrelated shear, three-dimensional correlated shear, and mesocyclone. An uncorrelated shear is a sufficiently strong circulation (as depicted by inbound and outbound mean radial velocities) but is detected on only one elevation angle within a storm. No symbol is graphically displayed when an uncorrelated shear is detected, but information concerning this circulation is available in the mesocyclone alphanumeric product. If a sufficiently strong circulation exists on two or more elevation angles within the same storm, but less than two of the features are symmetrical, then it is called a three-dimensional correlated shear and is displayed as a thin yellow circle. If the circulation is sufficiently large, detected on at least two elevation angles and is symmetrical, then the circulation is called a mesocyclone and is displayed as a thick yellow circle. Many mesocyclones in Oklahoma produce tornadoes, and nearly all generate some form of severe weather (e.g., hail or damaging winds) (Lemon et al. 1977). Range folding and incorrect velocity dealiasing may interfere with successful mesocyclone detection.

A **tornadic vortex signature** (TVS) is an intense azimuthal shear associated with a tornadic-scale rotation that is vertically correlated on at least two elevation angles *and is associated with an algorithm-defined mesocyclone.* When present, this product displays a red triangular symbol that pinpoints the potential location of a tornadic-scale rotation. Detection of a TVS is range limited due to beam broadening. The maximum range limit on the automated signature detection has been estimated to be about 100 km; however, forecasters have used indications of shear from mean radial velocity products to successfully identify tornado-bearing storms at more than 200 km.

Storm tracking information (STI) displays the previous, current, and projected locations of storm centroids (forecast and past positions are limited to one hour or less). The STI algorithm continuously computes its tracking errors and limits forecast positions to one hour or less depending on the magnitude of the errors. It is intended for application to individual storms, not systems such as lines or clusters. Forecast tracks are based on a linear extrapolation of past storm centroid positions. Therefore, storms traveling a curvilinear path or changing direction will not be accurately forecast.

The **storm structure** (SS) product is used to supplement graphical products. It provides an alphanumeric listing of storm structure attributes for each storm identified by the storm series subsystem. Examples for each identified storm include maximum reflectivity and its height, maximum storm velocity at the lowest elevation angle, storm-base height, storm-top height, and storm mass.

The **radar coded message** (RCM) is an alphanumeric coded message that will be used for the preparation of a national radar summary chart. It is composed of three parts that are produced automatically. Part A contains a tabular listing of alphanumerics that maps the 4-km x 4-km composite reflectivity product to a 1/16 limited fine mesh (LFM) grid. Part B of the message contains a single profile of the horizontal wind information derived from the output of the VAD algorithm. Part C contains remarks that can be augmented at the option of the user. An intermediate reflectivity graphic product is also produced simultaneously with part A to assist in local editing if desired.

6. Examples of some WSR-88D products

A description of the analysis products is made more meaningful if examples are shown. A small subset of the 39 categories of color products in the system are presented here. Instead of showing the best examples of significant features from different dates, products from the same date and time are portrayed. In this manner the products can be compared with one another and related features examined from different perspectives.

WSR-88D examples are from the Norman, Oklahoma, radar from base data collected on 1 September 1989 at 22:18 UTC. Information for other times close to 22:18 UTC is also presented on the precipitation accumulation and vertical wind profile products.

Thunderstorms moved from southern Kansas into northern Oklahoma during the morning hours of 1 September. Most of the thunderstorms throughout the day were associated with a frontal boundary, but outflow from these storms pushed slowly southward into central Oklahoma during the afternoon hours. Many of the figures focus on a storm located about 50 km north of the radar.

Figure 4 is a base reflectivity product at a 0.5° elevation angle with a 1° x 1.1-nm (2-km) resolution. This resolution allows the operator to see reflectivity returns out to 248 nm (460 km) and provides a first look at the "big picture." The 248-nm (460-km) range ring, state boundaries, major highways, and neighboring WSR-88D sites (some not yet installed) were selected to be associated with the product. The maximum reflectivity is 57 dB*Z*. The significant storms depicted in the Texas Panhandle (about 370 km from the radar) and in north-central Arkansas (about 445 km from the radar) illustrate the long-range capabilities of the system. An outflow boundary is discernable extending from just north to west of the radar.

Figure 5a looks similar to a base reflectivity product but is actually a composite reflectivity product. With the 0.54-nm (1-km) resolution, the range of the product is 124 nm (230 km), which is noted with the blue range ring. State and county boundaries and locations of airports (denoted by symbol "✈") are also included with the product. Note that the maximum reflectivity is 69 dB*Z* compared to 57 dB*Z* on the base reflectivity product, and higher reflectivities are much more evident throughout Fig. 5a. This indicates that high reflectivity regions are generally occurring at higher elevations than depicted in Fig. 4 and may be evidence of vigorous storm updrafts. The previously mentioned outflow boundary is also noted from north through west of the radar.

It is useful to display the three-dimensional features of a storm. One of the major strengths of the system is that it allows the user to create a four-panel reflectivity product using sectors from four different azimuthal sweeps all centered at the same location and magnified up to eight times.

Figure 5b is the composite reflectivity product centered near the intense storm north of the radar and magnified eight times. This magnification allows city names to be displayed and allows the operator to easily locate the most significant weather with respect to specific cities or parts of a county. Information from the storm series algorithms (mesocyclone, hail index, and storm tracking information) is overlaid on this product. The round yellow circle is a symbol for an algorithm-detected mesocyclone. The green unfilled triangle indicates that hail is probably occurring with this storm. The circle with the "x" in the middle (next to "04") is the storm centroid. The two dots to the west of the centroid depict the centroid location 15 and 30 minutes ago. The four tick marks to the east of the centroid indicate where the centroid is forecast to be located in 15, 30, 45, and 60 minutes. At the top of Fig. 5b is the combined attribute table. This table, which is created by the storm series algorithms, is available only with the composite reflectivity and composite reflectivity contour products. Storm attributes are listed for four storms, for example, the table indicates that the storm located north of the radar (number 04) is located 11°/28 nm (52 km) from the radar, has a maximum reflectivity of 66 dB*Z* at 39 300 ft (12.0 km), and is moving from 265°/17 kt (8.75 m s^{-1}).

The blue line that bisects the storm in Fig. 5b depicts a cross section selected by the operator. The slice selected is approximately perpendicular to the radar beam. Figures 6 and 7 illustrate cross sections of reflectivity, velocity, and spectrum width all taken for the slice selected in Fig. 5b. The reflectivity cross section (RCS) reveals the presence of a bounded weak echo region (BWER) (Chisholm and Renick 1972) on the right (southeast) side of the storm and the existence of 50+ dBZ reflectivities up to 55 000 ft (16.8 km). The radar currently samples only up to 19.5°, so the higher portions of storms close to the radar are not sampled. Although the radar echo cuts off abruptly, the storm top is likely higher than 60 000 ft (18.3 km). The high reflectivities aloft and the BWER are indicative of a severe thunderstorm (Lemon 1980). At this time, hail ranging from 1.9 to 2.2 cm in diameter was occurring with this storm.

The velocity cross section in Fig. 7a indicates a strong rotation. The red represents outbound radial velocities going into the page, while the green is indicative of inbound radial velocities coming toward the reader. The strongest velocities are 35 kt (18.0 m s^{-1}) inbound and $\geq$36 kt (18.5 m s^{-1}) outbound. The axis of the rotation is closely aligned with the BWER in Fig. 6. The rotational velocities (as inferred from the inbound and outbound mean radial velocities) and depth of the circulation along with their persistence from previous volume scans (not shown) are indicative of a mesocyclone. Although a tornado did not occur with this circulation, winds of 60 kt (30.9 m s^{-1}) occurred, destroying a mobile home and injuring a person inside.

The spectrum width cross section in Fig. 7b shows high spectrum width values of $\geq$12 kt (6.2 m s^{-1}) in the same location as the BWER in Fig. 6 and the mesocyclone axis in Fig. 7a. High spectrum width values are indicative of high variability of radial velocity estimates in the resolution volume and would be expected in the vicinity of a mesocyclone along with turbulence.

Figure 8 illustrates a weak echo region (WER) product centered on the same storm depicted in Figs. 6 and 7 (cross sections). On the left side of the grid of

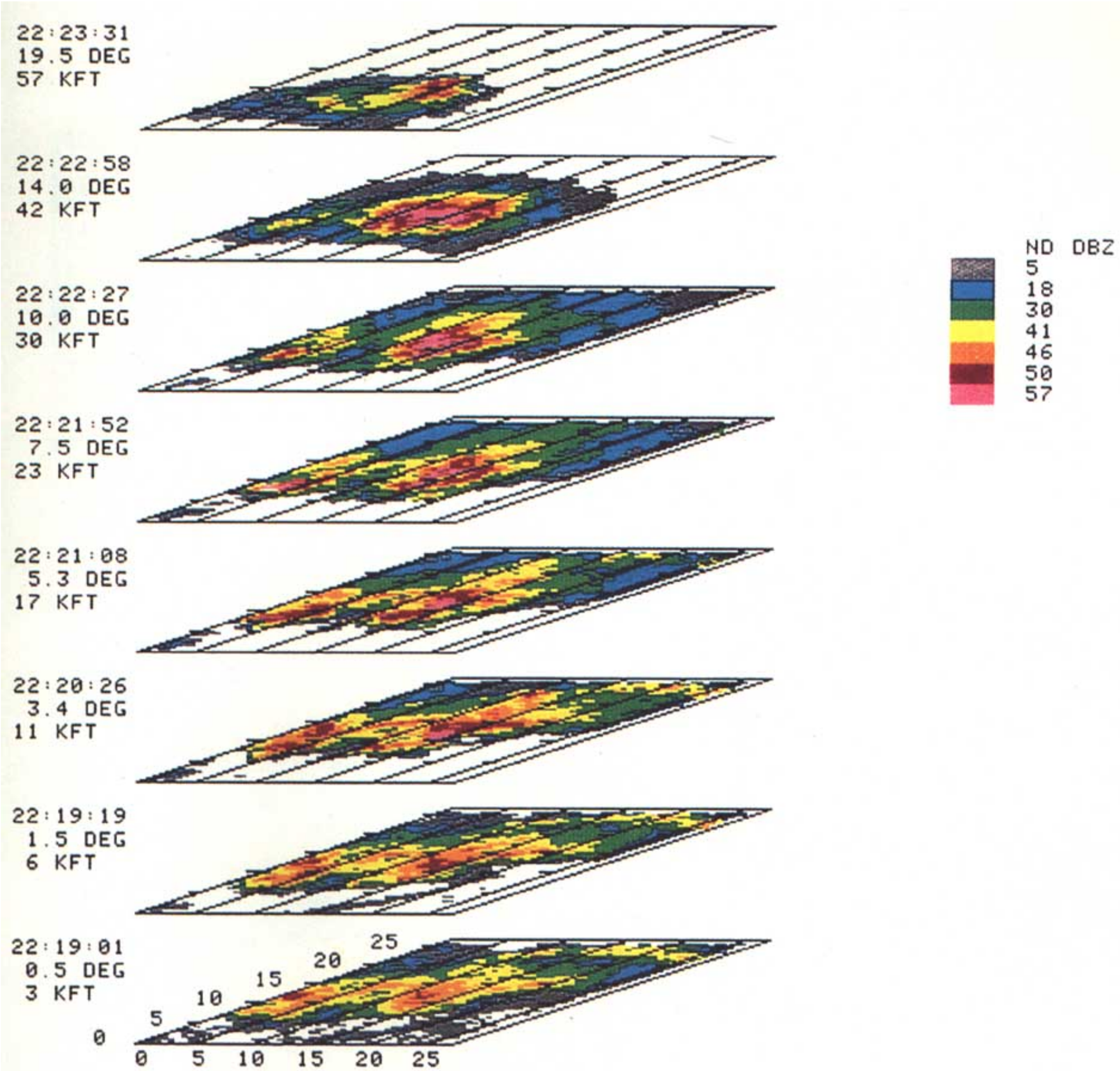


FIG. 8. Norman, Oklahoma, WSR-88D weak echo region product at 22:18 UTC 1 September 1989. Here 27 nm x 27 nm (50 km x 50 km) "windows" are centered at 12°/26 nm (48 km) from the radar. Resolution is 0.54 nm x 0.54 nm (1 km x 1 km). The beginning time of each azimuthal sweep for the associated elevation angle and the center height of each plane (MSL) are listed on the left side. The color table on the right depicts the intervals of reflectivity in units of dB*Z*.

this product, the beginning time of the azimuthal sweep, elevation angle, and the height (MSL) of the center of each plane are listed. The large area of 57+ dB*Z* at 42 000 ft (12.8 km) and 50+ dB*Z* up to 57 000 ft (17.4 km) is easy to discern. The high reflectivities aloft are indicative of a strong updraft.

It is useful to display the three-dimensional features of a storm. One of the major strengths of the system is that it allows the user to create a four-panel reflectivity product using sectors from four different azimuthal sweeps all centered at the same location and magnified up to eight times (8x). This product can be composed of any four elevation angles available in the antenna volume scanning strategy being employed at the time. The cover figure depicts 8x magnifications of reflectivity centered on the same storm illustrated in Fig. 8 (WER) for four elevation angles used on the WER product (0.5°, 5.3°, 10.0°, and 14.0°). Much more detail is apparent in the four-panel reflectivity figure compared to the WER product in Fig. 8. On the actual PUP workstation screen, a cursor is present at the same geographical location in each quadrant to assist the operator in establishing a frame of reference. This four-panel reflectivity product shows a

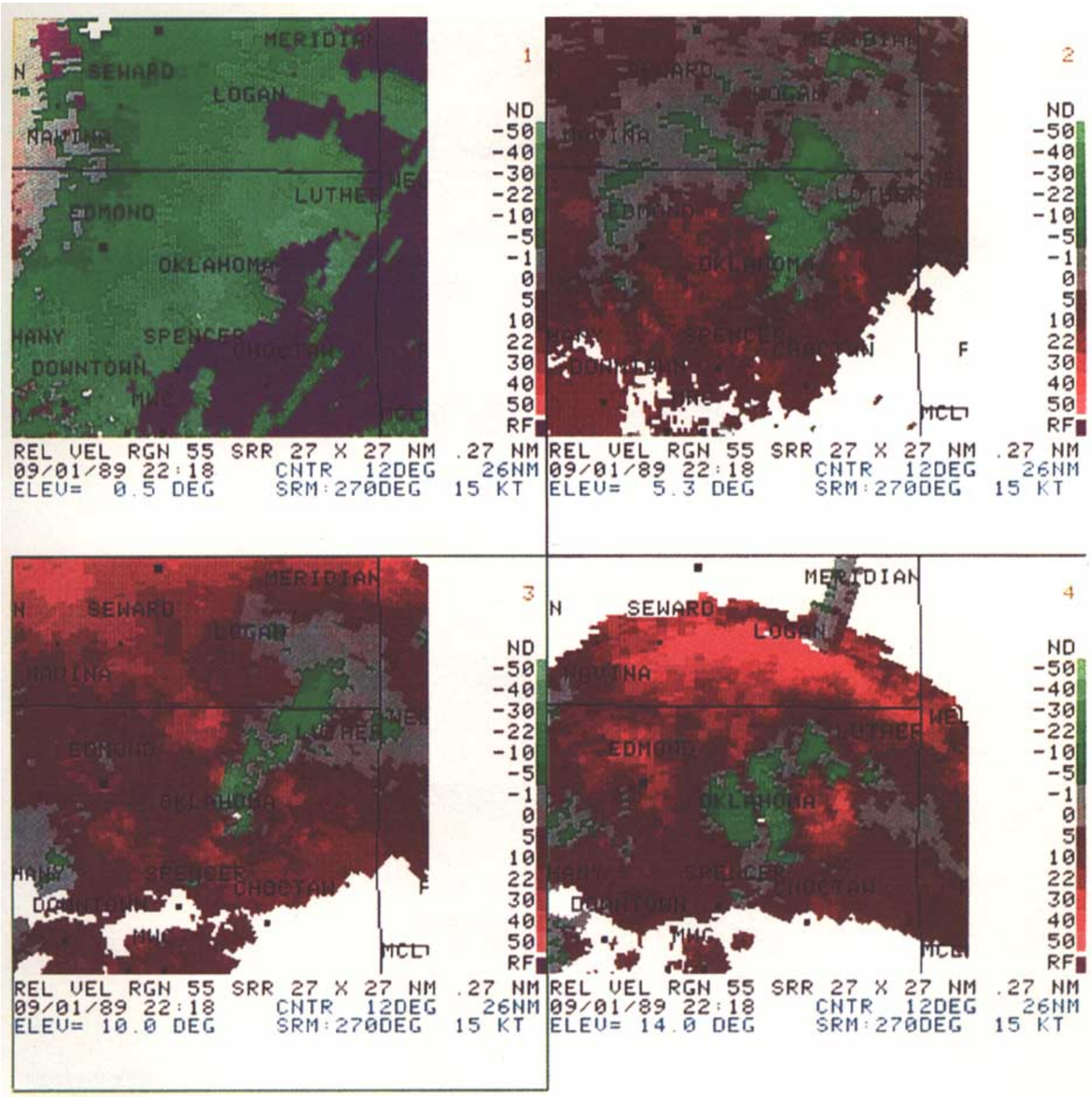


FIG. 9. Norman, Oklahoma, WSR-88D storm-relative mean radial velocity region products at 22:18 UTC 1 September 1989. Each "window" quarter panel covers 27 nm x 27 nm (50 km x 50 km). Resolution is 1° x 0.27 nm (0.5 km). Storm motion subtracted from base radial velocities was 270°/15 kt (7.7 m s^{-1}). The color tables on the right of each quarter panel depict the intervals of velocity in units of knots, and the "RF" denotes range folding. Green colors indicate radial velocities toward the radar, red colors indicate outbound velocities. Elevation angles, center locations, and maps displayed are the same as specified in the cover figure.

concavity on the east side of the storm at 0.5° that is indicative of strong low-level inflow, a weak echo of reflectivities surrounded by higher reflectivities at 5.3°, bounded above with higher reflectivities at 10.0° and 14.0°. This is another presentation illustrating a BWER. The city and county names are overlaid and specific towns near or in the path of the dangerous portion of the storm could be mentioned in warnings and statements.

With the WSR-88D, the forecaster can examine four panels of reflectivity and velocity simultaneously on two different display screens. In Fig. 9, a four-panel storm-relative mean radial velocity region (SRR) product has been created at the same elevation angles as the four-panel reflectivity product in the cover figure. The green colors indicate radial velocities coming toward the radar, while the red colors indicate velocities going away from the radar. In the lowest elevation angle (0.5°), most of the velocities are green, which is indicative of cool downdraft winds from the storm spreading southward toward the radar. The purple area indicates range folding.

Since the SRR subtracts storm motion, the shears associated with rotations can be more easily observed. At the three higher displayed elevation angles, the green/red couplet indicates that a counterclockwise circulation exists (since storm is north of the radar). The center of the circulation defined by the green/red couplet is located near the "MA" in the word "OKLAHOMA" in these three panels. This circulation extends from at least 17 000 ft (5.2 km) to 42 000 ft (12.8 km), as determined from heights corresponding with elevation angles in Fig. 8. Its rotational velocity, vertical continuity, and persistence (from previous volume scans—though not illustrated here) meet or exceed those of a mesocyclone.

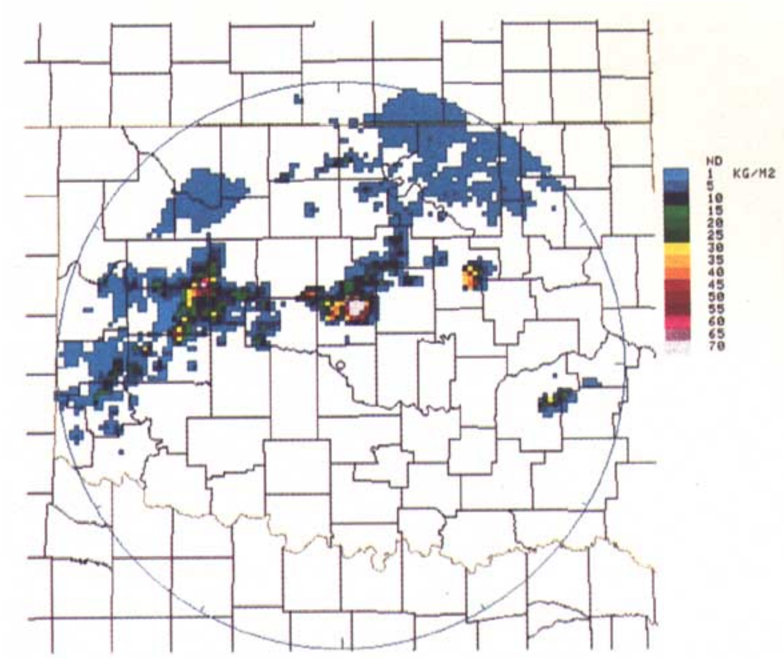


Fig. 10. Norman, Oklahoma, WSR-88D vertically integrated liquid product at 22:18 UTC 1 September 1989. Range of coverage is 124 nm (230 km) and resolution is 2.2 nm x 2.2 nm (4 km x 4 km). Maps displayed are 124-nm (230-km) range ring, state, and county boundaries. The color table on the right depicts the intervals of integrated liquid water in kilograms per meter squared. The maximum value is 90 kg m^{-2} located in the storm north of the radar.

Figure 10 illustrates the vertically integrated liquid (VIL) product. The forecaster must examine the environmental conditions to determine the "value of the day." Typically in Oklahoma, a VIL value of 55 kg m^{-2} or greater in early September would likely signify a storm that is producing severe hail ($\geq$1.9 cm). A large area of 70+ VILs are associated with the storm to the north of the radar. In fact, this storm's maximum VIL is 90 kg m^{-2}. This is consistent with the very high reflectivities noted aloft in both the RCS and WER products (Figs. 6 and 8). The expecta-

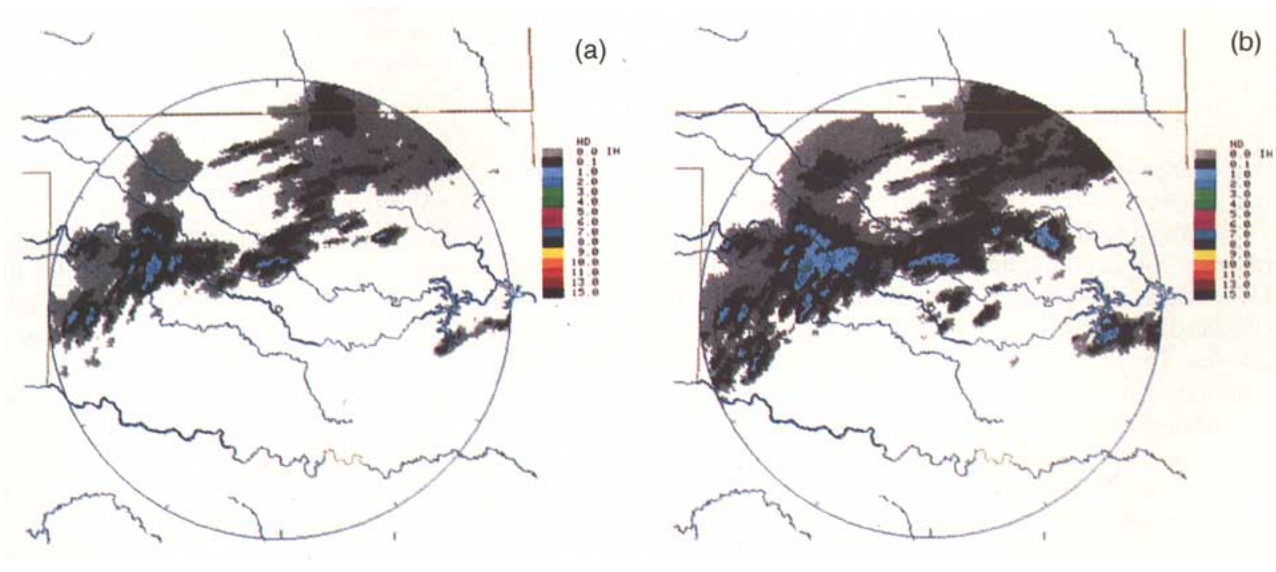


Fig. 11. Norman, Oklahoma, WSR-88D storm total precipitation product on 1 September 1989 for time intervals (a) 21:37–22:20 UTC and (b) 21:37–23:16 UTC. Range of coverage is 124 nm (230 km) and resolution is 1.1 nm x 1.1 nm (2 km x 2 km). Maps displayed are 124-nm (230-km) range ring, state boundaries, and rivers. The color table on the right depicts the intervals of estimated accumulated precipitation in inches. The maximum accumulations are 2.9 in (7.4 cm) inches (a) and 4.3 inches (10.9 cm) in (b).

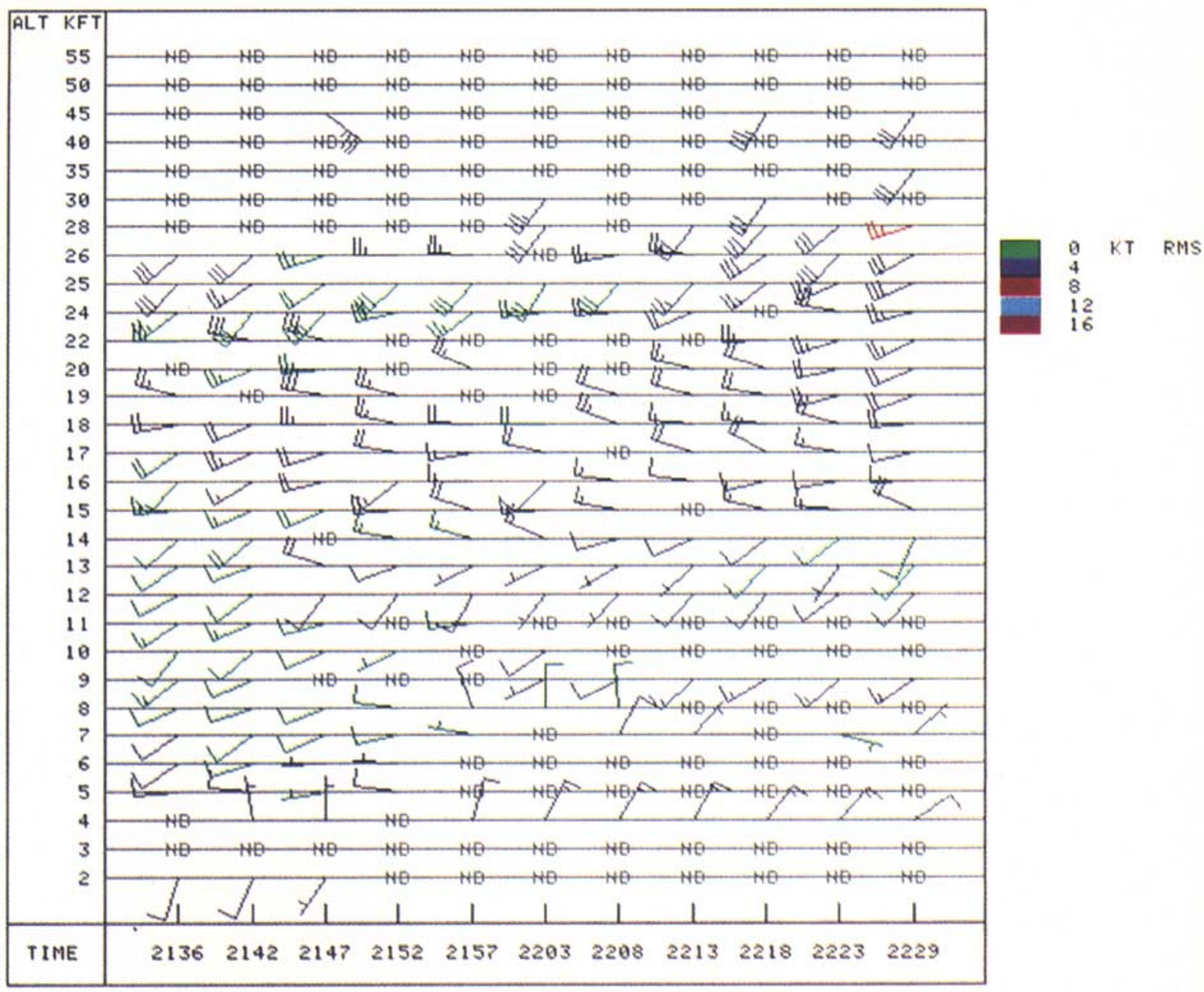


FIG. 12. Norman, Oklahoma, WSR-88D velocity azimuth display wind profile product on 1 September 1989 for 21:36 UTC to 22:29 UTC. Vertical axis is altitude in thousand feet. Here "ND" indicates no data. Wind barbs follow standard meteorological convention [e.g., wind at 45 000 ft (13.7 km) at 22:18 UTC is 212°/35 kt (18 m s^{-1})]. Color table on right depicts the root-mean-square error (in knots) for each wind estimate.

tion of significant hail with this storm verified as large hail (≥1.9 cm) fell from this storm for nearly 45 minutes.

Figures 11a,b illustrate the storm total precipitation product for accumulation intervals of 21:37–22:20 UTC and 21:37–23:16 UTC, respectively. Rivers are depicted to illustrate additional background maps capability. The regions where areal expansion of heavy estimated precipitation has occurred can be easily interpreted by comparing Figs. 11a and 11b. For instance, the areas exceeding 1.0 in. (2.54 cm) are much larger in Fig. 11b in several locations, including the storm depicted in previous figures to the north of the radar.

Figure 12 is a velocity azimuth display wind profile product. The winds were westerly at 5000 to 7000 ft (1525 to 2135 m) MSL between 21:36 and 21:52 UTC. The winds were generally northerly after 21:57 UTC at 4000 ft (1220 m) and 7000 ft (2125 m) as the aforementioned outflow boundary influenced the radar site area. Winds are missing (ND indicates no data) at several heights. The algorithm performs several quality control tests on the computed winds before they are displayed. The presence of the outflow boundary may have caused the tests to fail in the lower levels of the atmosphere.

7. Closing remarks

WSR-88D systems will provide a major improvement to existing weather radar detection capabilities. Principal improvements include Doppler capability, improved spatial resolution, and greater system sensitivity. In addition, the WSR-88D's data processing capabilities allow the generation of numerous meteorological and hydrological analysis products. Through the use of adaptable parameters, the system has been designed to be flexible in order to support the weather characteristics of any geographical and climatological region.

Meteorological and hydrological algorithms that process the reflectivity, mean radial velocity, and spectrum width data generate up to 39 categories of radar data analysis products every volume scan. But this represents only the initial operating capability of the system. These algorithms will be refined and improved, and new algorithms will be added throughout the life cycle of the WSR-88D system as new radar data analysis and processing concepts are developed and tested and the capacity and speed of system computers improves. The availability of recorded base data (level II) will play a crucial role in the development of system refinements and enhancements.

The products will not have equal importance at all regions of the country. For instance, the severe-storm-related products should play a more dominant role in the central plains than in the Pacific Northwest. The precipitation products, vertical wind profiles, and the numerous products that depict base data (reflectivity, mean radial velocity, and spectrum width) should be useful in all regions. The WSR-88D products will present observations of many weather phenomena that previously have not been discernible by operational meteorological instrumentation. This will result in better weather forecasts and a better understanding of the atmosphere.

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